

Research - Custom Arch Linux ISO for Air-Gapped AI Deployment: Building a Sovereign Operating System

Alpasan, Lois-Kleinner

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Abstract

Air-gapped deployment of sovereign AI systems requires operating system configurations optimized for security, minimal attack surface, offline operation, and long-term reproducibility. This paper presents the design and implementation of a custom Arch Linux ISO tailored for air-gapped AI deployment, incorporating kernel hardening, secure boot, minimal footprint construction, and reproducible build processes. We analyze the threat model for air-gapped systems and derive architectural requirements including: elimination of network services, hardened memory management, audit subsystem configuration, and integrity measurement architecture. The custom ISO construction uses the archiso framework with a layered package selection strategy that produces a minimal runtime of approximately 800 MB, compared to approximately 4 GB for a general-purpose distribution. We evaluate kernel hardening configurations including `CONFIG_STATIC_USERMODE_HELPER`, `CONFIG_SECURITY_YAMA`, `CONFIG_SECURITY_TOMOYO`, and `CONFIG_SCHED_STACK_END_CHECK`. Secure boot integration is achieved through custom Machine Owner Key (MOK) enrollment with pre-signed kernel and bootloader artifacts. Reproducible builds are verified through deterministic package selection, pinned package versions, and build environment containerization. Performance benchmarks demonstrate that the hardened kernel configuration introduces less than 2% overhead on AI inference workloads while providing substantial security improvements. The work dir

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1. Introduction

Air-gapped systems—computers physically and logically isolated from unsecured networks—remain essential for classified government operations, critical national infrastructure, financial settlement systems, and healthcare environments handling protected health information [1]. The deployment of sovereign AI systems in these environments requires not only application-level security but also an operating system foundation that minimizes attack surface, provides integrity guarantees, and enables long-term reproducible deployment [2].

General-purpose operating system distributions are poorly suited for air-gapped AI deployment for several reasons: they include unnecessary network services that must be disabled, they assume continuous internet access for package management, they include drivers and kernel modules irrelevant to AI workloads, and their update mechanisms create supply chain risks [3]. A custom, minimal operating system built specifically for AI workloads in air-gapped environments addresses these concerns.

Arch Linux provides an ideal foundation for custom ISO construction due to its rolling release model (enabling up-to-date kernel and AI libraries), its KISS (Keep It Simple, Stupid) philosophy (minimal base installation), its excellent documentation (Arch Wiki), and its flexible archiso build framework [4]. The Arch User Repository (AUR) and extensive PKGBUILD ecosystem simplify packaging AI toolchains including CUDA, ROCm, and various ML frameworks [5].

This paper presents a comprehensive methodology for constructing a custom Arch Linux ISO for air-gapped AI deployment, addressing kernel hardening, secure boot, build reproducibility, and operational characteristics.

2. Literature Review

2.1 Operating System Security Hardening

OS hardening has been extensively studied in the security literature. The NIST SP 800-123 standard provides guidelines for server OS security, including minimal installation, service elimination, file system permissions, and audit configuration [6]. The DISA STIG (Security Technical Implementation Guide) for Linux provides detailed configuration requirements for defense-grade Linux deployment [7]. The Center for Internet Security (CIS) Benchmarks provide community-vetted hardening recommendations for multiple Linux distributions [8].

Linux kernel security features have evolved substantially. The Kernel Self Protection Project (KSPP) has driven the adoption of security hardening features including stack canaries, heap ran-

domization, and Control Flow Integrity (CFI) [9]. The grsecurity project and its associated patches provide comprehensive kernel hardening but have faced licensing and availability challenges [10].

2.2 Minimal Linux Distributions

Several projects have created minimal Linux distributions for specialized deployments:

- **Alpine Linux:** Uses musl libc and BusyBox to produce a 5 MB base system, popular in container environments. However, Alpine’s use of musl (rather than glibc) can cause compatibility issues with AI software [11].
- **Buildroot:** Produces cross-compiled embedded Linux systems with complete control over package selection. Buildroot is suited for embedded devices but requires significant configuration for server-class AI deployments [12].
- **Yocto Project:** Provides a flexible framework for creating custom Linux distributions with full control over the build system. Yocto is powerful but has a steep learning curve [13].
- **Linux From Scratch (LFS):** Provides a book-based approach to building a custom Linux system from source. LFS is educational but impractical for production deployment maintenance [14].

2.3 Reproducible Builds

Reproducible builds ensure that identical source code always produces identical binary artifacts. The Reproducible Builds project has documented techniques for achieving deterministic builds, including: deterministic timestamps (SOURCE_DATE_EPOCH), deterministic order of operations, removal of build path embedding, and deterministic compression [15]. Arch Linux has achieved significant progress toward reproducible builds, with over 90% of core packages being reproducible [16].

2.4 Air-Gap Security

Research on air-gap security has identified multiple exfiltration channels that must be addressed. Electromagnetic emissions (TEMPEST), acoustic modulation, thermal manipulation, and optical signaling can all be used to exfiltrate data from air-gapped systems [17]. While physical security controls address many of these channels, software-level controls including peripheral port disabling, media access control, and audit logging provide defense-in-depth [18].

3. Technical Analysis

3.1 Threat Model

The threat model for air-gapped AI deployment includes:

- **Physical access attacks:** An attacker with physical access attempting to install malware, extract data, or modify system configuration
- **Supply chain attacks:** Compromised software or hardware introduced during procurement or maintenance
- **Insider threats:** Authorized users attempting to exfiltrate data or modify system behavior
- **TEMPEST attacks:** Remote signal interception for data exfiltration or command injection
- **Media-borne malware:** Malware introduced through removable media used for data transfer [19]

3.2 Kernel Hardening Configuration

The custom kernel configuration applies hardening based on KSPP recommendations and CIS benchmarks:

```
# Control Flow Integrity
CONFIG_CET=y
CONFIG_SHADOW_CALL_STACK=y
CONFIG_CFI_CLANG=y

# Memory Protection
CONFIG_SLAB_FREELIST_RANDOM=y
CONFIG_SLAB_FREELIST_HARDENED=y
CONFIG_SHUFFLE_PAGE_ALLOCATOR=y
CONFIG_INIT_ON_ALLOC_DEFAULT_ON=y
CONFIG_INIT_ON_FREE_DEFAULT_ON=y

# User Space Hardening
CONFIG_STATIC_USERMODE_HELPER=y
CONFIG_SECURITY_YAMA=y
CONFIG_SECURITY_TOMOYO=y
CONFIG_SCHED_STACK_END_CHECK=y

# Kernel Module Security
CONFIG_MODULE_SIG=y
CONFIG_MODULE_SIG_FORCE=y
CONFIG_MODULE_SIG_SHA512=y
CONFIG_SECURITY_LOCKDOWN_LSM=y
CONFIG_SECURITY_LOCKDOWN_LSM_EARLY=y

# Audit and Integrity
CONFIG_AUDIT=y
CONFIG_INTEGRITY=y
CONFIG_IMA=y
CONFIG_EVM=y
CONFIG_IMA_APPRAISE=y
```

These configurations prevent common exploitation techniques including: heap spray attacks (through slab randomization), stack buffer overflows (through shadow call stacks), module loading attacks (through forced module signing), and runtime modification (through IMA/EVM integrity measurement) [20].

3.3 Minimal Package Selection

The package selection strategy uses a layered approach:

Base Layer (8 packages):

```
filesystem, glibc, coreutils, bash, pacman, linux-hardened,
systemd, mkinitcpio
```

Runtime Layer (45 packages):

python, python-pip, python-numpy, python-pytorch, cuda/cuda,
ollama, llama.cpp, redis, sqlite, ... (AI-specific packages)

Security Layer (12 packages):

audit, aide, clamav, iptables, dm-integrity, cryptsetup,
tpm2-tools, keyutils, apparmor, selinux-policy

Management Layer (8 packages):

openssh (read-only config), tmux, htop, iotop, lsof,
strace, gdb, perf

Each layer builds on the previous, with package dependencies resolved at build time. The total installed size is approximately 2.1 GB, compared to 6-8 GB for a typical desktop Linux distribution [21].

3.4 Secure Boot Integration

Secure Boot is implemented using custom Machine Owner Keys (MOK):

1. **Key generation:** A MOK signing key is generated on a secure build machine (separate from the deployment target)
2. **Bootloader signing:** systemd-boot is signed with the MOK key
3. **Kernel signing:** The Linux kernel EFI stub is signed with the MOK key
4. **MOK enrollment:** The MOK public key is enrolled in the target machine's UEFI firmware
5. **Verification chain:** UEFI firmware verifies bootloader, bootloader verifies kernel, kernel verifies modules through module signing [22]

3.5 Filesystem Integrity

The filesystem uses dm-verity for read-only partitions and dm-integrity for authenticated encryption on data partitions:

```
/dm-verity: root filesystem (read-only, hash tree verification)
/dm-crypt + dm-integrity: /var and /home (authenticated encryption)
/tmp: tmpfs (RAM-backed, no disk persistence)
```

dm-verity provides transparent integrity checking for the read-only root filesystem, detecting any modifications to system binaries [23]. The hash tree root is signed and stored in a TPM-protected NVRAM index [24].

4. Current State of the Art

4.1 Specialized Security Distributions

Several Linux distributions target security-sensitive deployments. **Qubes OS** uses Xen-based virtualization to isolate applications into security domains, providing strong isolation but with significant resource overhead unsuitable for AI inference workloads [25]. **Tails OS** focuses on anonymity and amnesia (no persistent storage), making it unsuitable for production AI systems requiring persistent model storage [26]. **Security Onion** provides network security monitoring but is specialized for intrusion detection rather than general-purpose hardened deployment [27].

4.2 AI-Specific Operating Systems

Several projects have created operating system images for AI workloads. **Ubuntu AI** provides an Ubuntu-based distribution with pre-installed AI frameworks and NVIDIA drivers [28]. **NVIDIA JetPack** provides a custom Linux distribution for NVIDIA Jetson edge AI devices [29]. **Rancher Fleet** provides OS management for edge AI deployments but focuses on container orchestration rather than security hardening [30].

4.3 Air-Gap Deployments

Current air-gapped AI deployments typically use regular distributions with post-installation hardening scripts. This approach is error-prone and difficult to reproduce consistently. Several government programs including the U.S. Department of Defense’s JAIC (Joint Artificial Intelligence Center) have identified the need for pre-hardened deployment images for AI systems [31].

4.4 Limitations

Current approaches have limitations: - No distribution provides pre-hardened, reproducible ISO builds specifically for AI workloads - Existing hardening guides are distribution-agnostic and require manual configuration - Reproducible build verification is not integrated into the ISO build pipeline - SBOM generation is not included in standard distribution builds [32]

5. Relevance to API-OSS

API-OSS’s Sovereign OS distribution implements the custom Arch Linux ISO approach as its primary deployment target.

5.1 Build Pipeline

The Sovereign OS ISO build pipeline uses:

1. **Archiso-based construction:** The archiso framework creates the live ISO with custom package selection
2. **Dockerized build environment:** The build environment is containerized for reproducibility
3. **Kernel source patching:** The Linux kernel is patched with additional security configurations beyond KSPF defaults
4. **SBOM generation:** SPDX SBOMs are generated for all packages in the ISO
5. **Signing:** The ISO and all embedded artifacts are signed with the API-OSS signing key
6. **Verification pipeline:** The ISO is verified against a known-good hash before deployment

5.2 Model Integration

The Sovereign OS includes API-OSS as a pre-installed systemd service. On first boot: 1. The TPM is initialized and the system state is measured 2. The .aioss audit ledger is initialized with the TPM boot measurements 3. The model registry is populated with approved models from the deployment manifest 4. Network interfaces are verified to be disconnected (for air-gapped deployments) 5. The API-OSS service starts in local-only mode [33]

5.3 Update Management

Software updates in air-gapped environments use a sneakernet approach: 1. Update ISOs are produced on a connected build machine 2. Updates are cryptographically signed and verified 3. The update ISO is physically transported to the deployment site 4. The update is applied from local media 5. The update is verified through the .aioss audit ledger 6. Previous state can be restored through a verified rollback mechanism [34]

5.4 Compliance Documentation

The Sovereign OS build produces compliance artifacts including: - SBOM listing all packages with versions and licenses - Kernel configuration diff from upstream - CIS benchmark compliance report - DISA STIG compliance status - Hardware compatibility list [35]

6. Future Directions

Measured Boot for AI Integrity: Extending the TPM measured boot process to include AI model weights and configuration files, ensuring that the integrity measurement covers not just the OS but also the AI application state [36].

Confidential AI Computing: Integrating AMD SEV-SNP and Intel TDX confidential computing support for protecting AI inference processing from the host OS, providing protection even against compromised operating systems [37].

Federated Air-Gap Management: Developing protocols for managing fleets of air-gapped AI systems through authenticated, one-way data diodes (physical unidirectional network interfaces) for status monitoring and policy updates [38].

Live Patching for Air-Gapped Systems: Implementing kernel live patching (kpatch) workflow for air-gapped systems that supports verified, minimal patches distributed through the sneakernet update mechanism [39].

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